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A novel macro model of traffic flow with the consideration of anticipation optimal velocity

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HIGHLIGHTS

- A new macro model of traffic flow is proposed by incorporating anticipation effect.
- The stability of traffic flow with anticipation effect term has been explored.
- The numerical simulation is carried out to confirm the validity of anticipation effect.
- The results show that the anticipation effect can improve the stability of traffic flow.

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ABSTRACT

In this paper, a novel macro model which can investigate wide moving jams is derived from car-following model by applying the relationship between the micro and macro variables with the consideration of anticipation optimal velocity on single lane. The theoretic analysis and numerical simulation show that the new macro model of traffic flow can correctly reproduce common evolution of shock, rarefaction wave and local cluster effect under small perturbation, which shows that the congested traffic patterns about wide moving jam propagation are in accordance with empirical results. Furthermore, the results uncover that the anticipation effect can smooth the front of the shock wave and the rarefaction wave, which means that anticipation effect hasten the diffusion process of congregate in the shock wave and dissolution in rarefaction wave. The key improvement of this new macro model over the previous ones lies in the fact that the anticipation traffic behaviors can improve the stability of traffic flow with the consideration of the proper anticipation effect.

1. Introduction

In recent years, traffic jam has an important influence on modern society since traffic problem becomes more and more serious with the increase of traffic flux. Therefore, many traffic models have been constructed to investigate various complex traffic phenomena. The car-following model and the macro continuum model of traffic flow are two favorable types of traffic models describing the microscopic traffic behavior of an individual driver and the macro traffic behavior of collectivity respectively. In the past, car-following models [1–19] are fashionable traffic models to descript human driving behaviors. In view of macro traffic model, on the basis of LWR model [20,21], a number of high-order continuum models have been presented to overcome the deficiencies of the LWR model [22–31]. Furthermore, three-phase traffic theory [32–34] including free flow, synchronized flow and wide moving jam has attracted more and more broad interest to investigate traffic phenomena. And the congested traffic covers the synchronized flow and wide moving jam phases.

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Although the fundamental diagram theory cannot describe synchronized flow, it can simulate wide moving jam propagation corresponding to empirical results, which has firstly been found by Kerner and Konhäuser when they studied a version of Payne-model [34,35]. Also, the car-following model and the LWR model cannot describe traffic breakdown as observed in real traffic, but the models adapt to the analytical study of wide moving jams deeply. In particular, a few car-following models [1–8] investigated reaction times to anticipate the future driving behaviors. However, the anticipation effect of optimal velocity has little considered in previous macro traffic models. In fact, a driver often adjusts his speed to his anticipation of optimal velocity according to observed traffic conditions. In this paper, a new macro model of traffic flow with an anticipation term is derived from a new car-following model with the consideration of the anticipation effect by applying the relationship between the micro and macro variables on a single lane highway. Theoretic analysis and numerical simulation indicate that the new macro model can reproduce complex traffic phenomena and the anticipation term can improve macroscopic traffic characteristic features of wide moving jam.

2. Model

Car-following models describe the run processes based on the idea that the motion of each vehicle responds to his leading vehicle. In 1995, Bando et al. [9] presented an OVM that the driver adjusts his acceleration by attaining to an optimal velocity. Hereafter, to overcome the shortage of the OVM, Jiang et al. [8] developed a full velocity difference model (FVDM) by considering velocity differences. However, in reality, the driver often adjusts his acceleration by anticipating traffic conditions. Therefore, a new car-following model [8] is developed with the consideration of anticipation optimal velocity on single lane as follows:

$$\frac{\mathrm{d}v_n(t)}{\mathrm{d}t} = a\left[V(\Delta x_n(t+\alpha T)) - v_n(t)\right] + \lambda \Delta v_n \tag{1}$$

where $\Delta x_n = x_{n+1} - x_n$ and $\Delta v_n(t) = v_{n+1} - v_n$ represent the distance headway and the velocity difference between the leading vehicle $n+1$ and the following vehicle n respectively; $x_n(t)$ and $v_n(t)$ are the position and velocity of car n at time t respectively; τ is the delay time and $a = 1/T$ represents the sensitivity of a driver; λ means the response coefficient to the velocity difference; $\alpha \geq 0$ and $V(\Delta x_n(t+\alpha\tau))$ show the anticipation coefficient and the anticipation optimal velocity. Eq. (1) shows that the driver adjusts driving acceleration not only according to his own running car velocity $v_n(t)$ and velocity difference $\Delta v_n(t)$, but also according to anticipation optimal velocity at time $t + \alpha\tau$ after delay time τ in advance. The extended model accords with FVDM at $\alpha = 0$.

In order to develop the corresponding macroscopic continuum model, we suppose that the state of the car n at position x denotes the average traffic condition at region $[x - \Delta/2, x + \Delta/2]$ by transforming the discrete variables of individual vehicles into the continuous flow variables. Here Δ corresponds to Δx in car-following theory and varies with different inter-vehicle distance headways between different successive vehicles. Therefore, the switch is adopted by transforming the above micro variables into the macro ones as follows [36]:

$$\begin{aligned} &v_n \to u(x,t), \qquad v_{n+1} \to u(x+\Delta,t)\\ &V(\Delta x_n(t+\alpha\tau)) \to u_e(\rho(t+\alpha T, x+\Delta/2)), \qquad a = \frac{1}{T}, \qquad \lambda = \frac{1}{\tau} \end{aligned} \tag{2}$$

where $\rho(x,t)$ and $u(x,t)$ represent the macro density and speed at the place (x,t) respectively; $u_e(\rho(t+\alpha T, x+\Delta/2))$ means the anticipation equilibrium speeds defined by the density $\rho(t+\alpha T, x+\Delta/2)$ at time $t+\alpha\tau$ and a location $x+\Delta/2$, i.e., exactly in between the two cars. T and τ are the relaxation time and the time needed for the backward propagated disturbance to travel a distance of Δ. Then Eq. (3) can be represented by

$$\frac{\mathrm{d}u}{\mathrm{d}t} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \frac{u_e(\rho(t+\alpha T, x+\Delta/2)) - u}{T} + \frac{1}{\tau}[u(x+\Delta,t) - u(x,t)]. \tag{3}$$

For simplicity, make the Taylor expansion of the variables including $\rho(t+\alpha T, x+\Delta/2)$, $u_e(\rho(t+\alpha T, x+\Delta/2))$ and $u(x+\Delta,t)$, and neglect the nonlinear terms, i.e. [37]

$$\begin{cases} \rho(t+\alpha T, x+\Delta/2) = \rho(x,t) + \alpha T\dfrac{\partial\rho}{\partial t} + \dfrac{\Delta}{2}\dfrac{\partial\rho}{\partial x}\\ u_e(\rho(t+\alpha T, x+\Delta/2)) = u_e(\rho(x,t)) + \alpha T u_e'\dfrac{\partial\rho}{\partial t} + \dfrac{\Delta}{2}u_e'\dfrac{\partial\rho}{\partial x}\\ u(x+\Delta,t) = u(x,t) + \Delta\dfrac{\partial u(x,t)}{\partial x}. \end{cases} \tag{4}$$

Substituting Eq. (4) into Eq. (3) and combining the conservative equation, we derive a new macro model as follows:

$$\begin{cases} \dfrac{\partial\rho}{\partial t} + \dfrac{\partial(\rho u)}{\partial x} = 0\\ \dfrac{\partial u}{\partial t} + (u - c_0)\dfrac{\partial u}{\partial x} = \dfrac{u_e(\rho) - u}{T} + \alpha u_e'\dfrac{\partial\rho}{\partial t} + \dfrac{\tau}{T}\dfrac{c_0}{2}u_e'\dfrac{\partial\rho}{\partial x} \end{cases} \tag{5}$$